Establishing conservation buffers using precision information

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Abstract: Conservation buffers, such as filter strips and riparian forest buffers, are widely prescribed to improve and protect water quality in agricultural landscapes. These buffers intercept field runoff and retain some of its pollutant load before it reaches a waterway. A buffer typically is designed to have uniform width along a field margin and to intercept runoff that flows uniformly to it. However, spatial analysis of field conditions and runoff patterns indicate that more runoff is likely to flow to some locations along a field margin than to others which can substantially limit a buffer's effectiveness. We propose that precision conservation, the use of precision spatial information, technologies, and procedures to implement conservation practices, can be used to improve the design of buffers and ensure their effectiveness. Precision conservation can integrate detailed landscape data with mathematical models in a geographic information system. We can then analyze spatial patterns of runoff and design variable-width buffers that precisely match the needs of every location along a waterway. Greater cost of precision conservation is offset partly by greater water-quality benefit from each acre of buffer. Many of the required data sources and modeling components already exist, substantial improvements are possible that can produce even greater conservation efficiency.

Keywords: Buffer design, filter strip, precision agriculture, precision conservation, riparian buffer, water quality

High-yield agricultural methods need to be better integrated to reduce accompanying environmental problems. These methods, including tillage and chemical amendments over extensive land areas, are critical to producing adequate food to support the global human population. At the same time, however, these methods expose the land to soil loss that threatens our ability to sustain high yields. Agricultural lands produce sediment, as well as nutrients and chemicals in runoff, that degrade water quality, accelerate sedimentation, impair recreation, and stress ecosystems.

High-yield methods include managing large blocks of land (e.g., whole fields and farms) uniformly to simplify farming operations. But land conditions vary at smaller scales that substantially affect resource degradation and the effectiveness of conservation practices. Precision conservation offers a way to improve soil conservation and reduce environmental degradation associated with high-yield agriculture (Pierce and Nowak, 1999). Precision conservation is the use of precision spatial information, technologies, and procedures to implement conservation practices (Berry et al., 2003). It enables the evaluation of smaller-scale patterns of land conditions, leading to management recommendations that are tailored to suit site-specific conditions and needs (National Research Council, 1997).

Precision conservation is made possible through the use of emerging spatial information and technologies, such as global positioning systems (GPS), detailed digital landscape data, spatially-explicit mathematical models, geographic information system (GIS) software, and inexpensive computers capable of calculation-intensive analyses. Employing these tools enables a more precise fit between conservation needs and control practices (Berry et al., 2003). In this paper, we propose to show how precision conservation can improve the design of conservation buffers to protect and improve water quality in agricultural landscapes.

Precision conservation aids buffer design

Filter strips and riparian forest buffers are areas of permanent vegetation located between agricultural fields and the waterways to which they drain. These buffers intercept and slow runoff, which promotes the deposition of sediment and sediment-bound pollutants, and the infiltration, immobilization, and transformation of dissolved pollutants. Cleaner water then passes on to the waterways. These buffer practices are key elements in U.S. Department of Agriculture (USDA) conservation programs and initiatives (e.g., Conservation Reserve Enhancement Program, Environmental Quality Incentives Program, National Conservation Buffers Initiative).

In typical applications, filter strips and riparian forest buffers are designed as strips of uniform width along waterways. Wider buffer strips provide a greater level of pollutant control (e.g., Dillaha et al., 1989; Dosskey, 2001; Magette et al., 1989; Patty et al., 1997; Schmitt et al., 1999). This approach presumes that field runoff is uniformly distributed and that a uniform level of pollution control is obtained along the buffer (Figure 1a).

Field runoff, however, is commonly nonuniform, converging on some parts of the field margin and diverging from others because of uneven topography and patterns of soil conditions and farming practices (Figure 1b; Dillaha et al., 1986, 1989; Dosskey et al., 2002; Fabis et al., 1993). Buffers are less effective for sediment and nutrient retention where converging, or concentrated, flow occurs (Table 1; Daniels and Gilliam, 1996; Dickey and Vanderholm, 1981; Dillaha et al., 1986, 1989; Dosskey et al., 2002). Other areas of buffer that receive little or no runoff contribute little to controlling total pollutant runoff from the field. Under these conditions, uniform-width buffers are often not very effective or efficient, and are unlikely to meet expectations for water-quality protection.

Greater spatial discrimination can improve buffer design by letting managers vary buffer width to match smaller-scale spatial patterns

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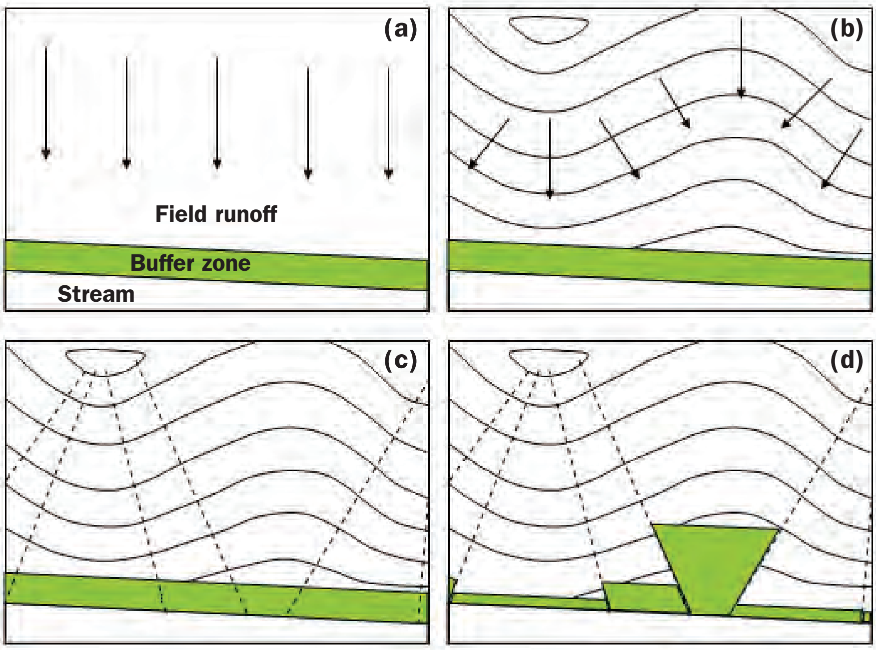
Figure 1

Diagrams of crop-field runoff patterns, topographic contours, and alternative buffer designs: (a) uniform runoff flow to a uniform-width buffer; (b) non-uniform runoff flow to a uniform-width buffer; (c) non-uniform runoff areas and the corresponding uniform-width buffer locations to which they flow; (d) non-uniform runoff areas and the corresponding variable-width buffer areas to which they flow. Both (a) and (d) yield an approximately-constant level of pollutant filtering along the entire length of the buffer.



of runoff. Runoff load and flow-direction patterns can be predicted using mathematical models with soils and topographic data. Other models can estimate the size of buffer required to achieve a desired level of control under different input loads. Using these tools, buffers can be located and sized more precisely to match spatial patterns of runoff load along a field margin and achieve a consistent, desired level of control. This precision conservation approach can enhance buffer projects by placing more buffers where there is greater need and by yielding better prediction of effectiveness.

Designing variable-width buffers

The concept of designing variable-width buffers to match spatially variable input loads has been discussed recently. Bren (1998, 2000) developed a method for use in forested landscapes. That method consists of dividing the length of a waterway into segments and evaluating the buffer needs of each segment separately with the goal of achieving a constant ratio of buffer area to runoff area that drains to it. Dosskey et al. (2002) extended the buffer-area-ratio approach to quantify the level of control and applied it to agricultural landscapes.

As an agriculture-specific buffer design process, this approach has four general steps. 1) Divide the field margin into segments and identify the field area that contributes runoff to each segment; 2) Compute the runoff load from that area; 3) Compute the width of buffer needed to achieve a desired level of control on that load; and 4) Locate on a map the field margin boundary that yields this width from the waterway.

Runoff-contributing areas are usually irregular in shape, especially in rolling topography (Figure 1c). Flow tends toward natural swales in the landscape and away from ridges. This general pattern can be modified by microrelief in the form of furrows and ridges associated with farming operations (Brothers, 2001; Ludwig et al., 1995; Souchere et al., 1998). Two approaches may be suitable for delineating field-margin segments and runoff-contributing areas. In the first, the field margin can be divided into segments of similar length and the topography analyzed to determine the field area that flows to each segment. In the second, large fields can be subdivided into small catchments that flow to identifiable portions of the field margin (Dosskey et al., 2002).

Runoff loads from field areas to individual segments of field margin can be computed using existing models. For example, the Revised Universal Soil Loss Equation (Renard et al., 1997), the Soil Conservation Service (SCS) Curve Number method (USDA-SCS, 1968), and the CREAMS model (Knisel, 1980) are designed to predict water, sediment, and chemical runoff from cultivated fields under varying conditions soil type, slope, field size, farming practices, and climate. The calculations can be simplified by using constant values for soil type, slope, field size, or farming practices that vary within narrow limits. For the climate variable,

Table 1. Estimated sediment filtration by riparian buffers for uniformly and non-uniformly distributed runoff flow on four farms in southeastern Nebraska. Values were obtained using VFSMOD for a 10-year frequency storm event based on observed flow path, soil, and buffer conditions along 1446 to 2069 m of field margin on each farm (Data from Dosskey et al., 2002).

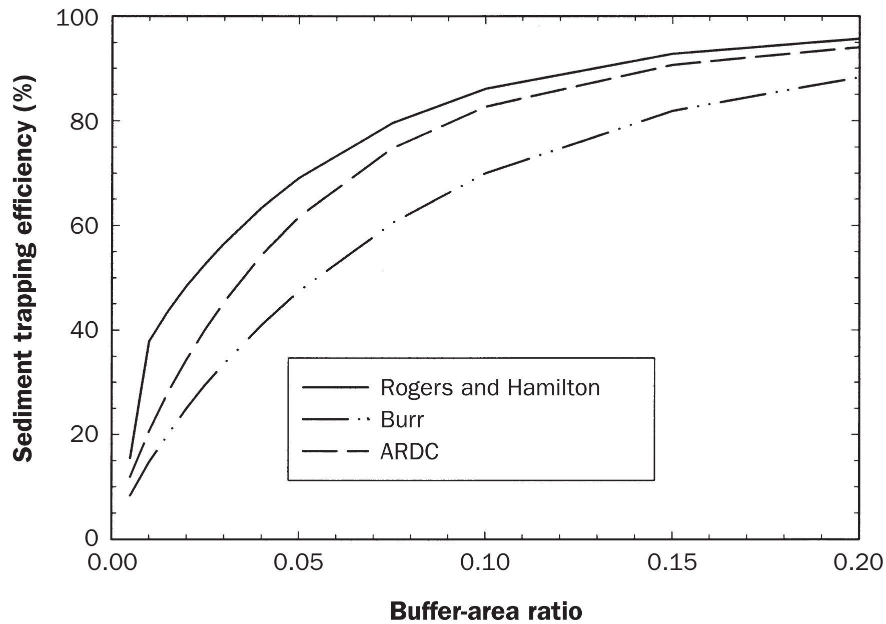
		Slope		Percent sediment retained	
Farm	**Setting**	**Mean**	**Range**	**Uniform**	**Non-uniform**
Rogers	Hills, dryland row crops	2.0	1-5	99	43
Burr	Hills, dryland row crops	3.8	1-9	67	15
ARDC	Plains, dryland row crops	2.3	1-4	59	23
Hamilton	Plains, furrow-irrigated crops	2.0	1-6	41	34
			Mean =	67	29

calculations should be based on a standard size and type of storm event that is appropriate for a given area. A large model-storm event is recommended for water-quality work since most erosion and pollutant transport occurs during infrequent large storms (Larson et al., 1997). In relatively uniform landscapes where all of the variables are approximately constant, runoff load is directly proportional to size of the runoff area (e.g., Bren, 1998). In complex landscapes, there can be substantial variability from one runoff area to another that must be accounted for in computing runoff load to individual segments of a field margin (Dosskey et al., 2002).

Irregular shape of runoff areas presents some uncertainty for predicting runoff load using some existing models. Some mathematical models assume that runoff occurs from a rectangular field. It is not known how much departure from rectangular can be allowed before estimations of runoff load become seriously over- or under-predicted by these models.

The design width of a buffer depends on the input load, the filtration characteristics of the buffer area, and the desired level of control. For surface runoff, buffer filtration characteristics include slope, permeability of the soil, and surface roughness provided by vegetation and debris. Existing buffer-filtration models, such as the University of Kentucky Sedimentation Model (e.g., Barfield et al., 1979; Hayes et al., 1979) and the Vegetative Filter Strip Model (VFSMOD; Muñoz-Carpena and Parsons, 2000), compute level of control for a given width of buffer, filtration characteristics of the buffer, and input load. These models also can be applied to compute a buffer width that provides a desired level of control. For example, Dosskey et al. (2002) used VFSMOD to generate a function for sediment-trapping efficiency (i.e., percent of input load retained in the buffer) based on the ratio of buffer area to field runoff area (Figure 2). Using such a function, buffer width can be determined by applying this buffer area along a predetermined length of field margin for a runoff area. A different function may be needed for fields or farms where there are substantial differences in soil type, slope, and slope length conditions (Figure 2; Dosskey et al., 2002). This approach improves on the work of Bren (1998), since it accounts for a greater number of variables and provides a quantitative estimate of level of control. This modification of an existing model can be used to determine the design width needed for each buffer segment to provide a constant level of control along a field margin, where runoff load can vary from segment to segment (Figure 1d).

Figure 2
Relationship between sediment trapping efficiency (i.e., percent of input load retained by the buffer) and buffer-area ratio developed using VFSMOD for conditions on four farms in southeastern Nebraska. Buffer-area ratio = (Buffer area / field runoff area). (Figure from Dosskey et al., 2002.)



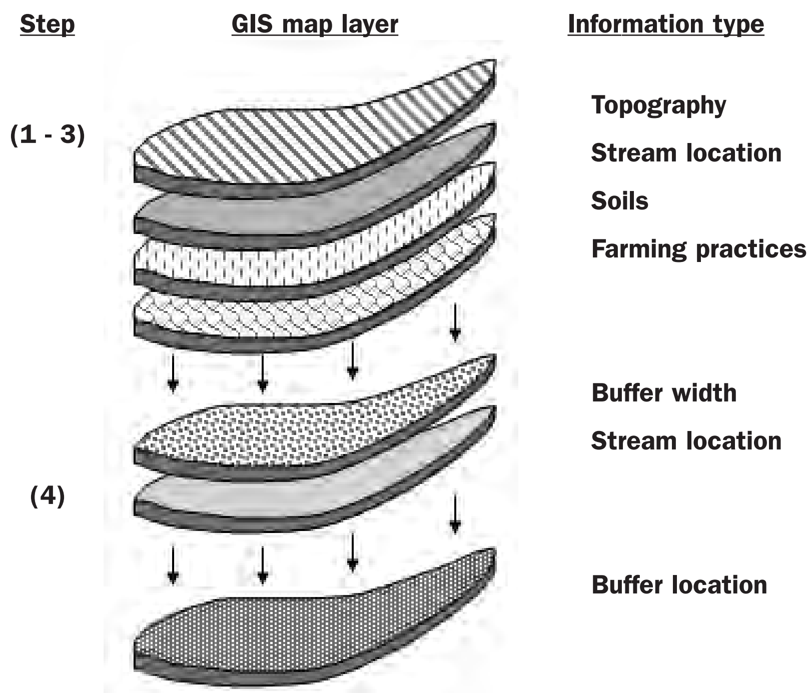
After determining design widths for all segments of buffer, it is necessary to identify on a map the location of the field margin boundary that will yield buffers of appropriate widths for all segments. An accurate map showing the precise location of the adjacent waterway is required. The resulting field margin boundary can be quite uneven from one segment to another, especially in rolling topography (Figure 1d). Abrupt boundary transitions between buffer segments can be smoothed, but smoothing should avoid reducing buffer width in locations where heavier runoff loads occur.

Variable-width buffer design by precision conservation

Analysis, modeling, and mapping can all be conducted within GIS software on commonly available computers. Many of the required data layers and digital technologies already exist for applying a precision conservation approach to the design of filter strips and riparian forest buffers (Figure 3). Topographic information is crucial for identifying runoff-contributing areas and for calculating field runoff load and buffer filtration capability. Digital topographic maps based on digital elevation models are becoming commonly available. Terrain analysis models can use digital elevation model-based topography to identify runoff-contributing areas and calculate slopes for use in field-runoff and buffer-filtration models.

The level of topographic accuracy, however, can be important for obtaining an accurate terrain analysis. In one comparison (Brothers, 2001), estimates of runoff-contributing area to a segment of existing filter strip ranged from 0.94 ha (2.3 ac) using a U.S. Geological Survey 30-m digital elevation model to 5.66 ha (14.0 ac) based on a laser survey of the field (Table 2). If the filter strip had been designed using the 30-m digital elevation model, it would be undersized because the input load would be greatly underestimated. Further analysis used the 30-m digital elevation model in conjunction with a statistical technique that accounts for microrelief associated with row crop direction. This technique yielded a runoff area of 2.97 ha (7.4 ac), suggesting that statistical procedures may help overcome some of the inaccuracy associated with using coarse topographic data. These results also demonstrate the high degree of sensitivity of flow patterns to macro- and micro-topography.

Figure 3
Precision buffer design using a GIS framework. Steps 1-3 integrate site condition data and mathematical models to develop estimates for buffer width for each segment of field margin. Step 4 compares those results with stream location to produce a map containing the location of the designed field margin-buffer boundary.



A major source of inaccuracy in published topographic data is recent change in field relief. For example, land-shaping operations and drainage improvements can result in large changes in farm and field runoff patterns (Dosskey et al., 2003). Furthermore, micro-relief patterns caused by tillage and planting direction can change substantially from year to year. Extensive modification of the topography of fields and buffer zones may then render some sources of even recent elevation data obsolete.

Soil surveys available from the USDA Natural Resources Conservation Service can provide soil data useful for estimating runoff load and buffer filtration. Soil-survey data is now available in digital spreadsheets (e.g., STATSGO, SSURGO; USDA, 1994). Corresponding digital maps of soil map units that integrate with GIS are also available for most states in the SSURGO database. Before applying soil-survey information to buffer design along individual fields, however, it is important to verify soil and slope descriptions and map unit boundaries. In some instances, substantial soil erosion, land shaping, or other soil disturbance have occurred since the survey was conducted and important field runoff and buffer filtration characteristics have changed.

An accurate map of waterway location is needed to convert buffer-width determinations into a location of the buffer/field-margin boundary. A recent geo-referenced, digital aerial photograph is probably the best way to determine waterway location. Many published stream-network maps are probably too inaccurate to be useful (Walker and Willgoose, 1999). The maps may be based on analysis of low-precision topographic data (McMaster, 2002) and/or may not identify man-made modifications to topography, channel locations, and other drainage features. Once a geo-referenced boundary is located on a map, a GPS can be used to find and follow that location on the ground, thus identifying where buffer vegetation should be installed.

Precision conservation creates an opportunity for optimizing buffers with other conservation practices. The design width of a buffer can be reduced by instituting other practices in the field that reduce runoff load and disperse its flow to the field margin. If a buffer is designed in concert with in-field conservation practices, a manager has some flexibility to find a balance between in-field and buffer practices that better suits the need of an individual landowner. Precision conservation facilitates such optimization by assembling the required tools in a computer platform that can perform the numerous computations required to conduct optimization analyses.

Limitations and other considerations

The precision-conservation approach that we propose does not strictly conform to USDA standards for filter strip and riparian forest buffer practices. Those standards require that concentrated runoff flow be dispersed by other means before a filter strip or riparian forest buffer is appropriate. In contrast, we propose the buffer *itself* be designed to address concentrated runoff flow by varying its width to match uneven patterns of runoff along a field margin. This alternative approach is made possible by the technologies that underpin precision conservation.

Table 2. Estimated area of field draining to a filter strip using three different topographic data sources and one topographic source combined with statistical evaluation that accounted for row crop ridge and furrow direction. The field area sloped toward the east and north at 0.4 to 4.2 percent, crop rows ran south to north, and the buffer was located on the north side of the field. (Data from Brothers, 2001).

Data source	Vertical accuracy (m)	Area of field draining to the filter strip (ha)
Laser survey	+/- 0.08	5.66
SCS* contour map	+/- 0.15	3.87
USGS† 30m DEM‡	+/- 1.5	0.94
USGS 30m DEM combined with discriminant analysis		2.97

* **Soil Conservation Service**
† **U.S. Geological Survey**
‡ **Digital elevation model**

The precision-conservation approach to buffer design is relatively expensive compared to the current USDA approach. Computers, digital data sets, analytical software, and GPS equipment required to conduct the precision-conservation approach add substantial cost to the design process.

On the other hand, the high cost of conducting precision conservation can be offset by 1) reduced or eliminated costs of additional practices to disperse concentrated-runoff flow; 2) reduced cost of installing buffers by requiring less total area of land in buffer to achieve the same level of water-quality benefit; 3) reduced maintenance costs associated with removing uneven sediment buildup by getting better distribution of trapped sediment along the buffer zone; and finally 4) reduced societal costs associated with better control and prediction of water quality.

Other economic efficiencies can be obtained by spreading the costs of precision-conservation equipment and software over a broader range of applications and larger areas. The same tools can be used to design and locate in-field buffers, flow-dispersion structures, and other erosion- and runoff-control practices. Furthermore, these tools are the same ones used for conducting precision agriculture (Pierce and Nowak, 1999). Precision conservation can also be used to design buffers on pasture lands and other livestock areas, although models that predict microbe trapping by buffers have not yet been developed. On the whole, buffer design by precision conservation may not be economical for individual smaller farms. It is more likely to be adopted by larger farms and cooperatives already engaged in precision agriculture, or to protect waterways that have particularly high value.

The wavy field margin that can result from buffer design using precision conservation represents another potential drawback. Wavy margins are more difficult to farm against than straight margins, so farmers may avoid adopting the precision-conservation approach in favor of the convenience of rectangular field geometry. Under these circumstances, in-field conservation practices may be required to disperse concentrated flows and create uniform runoff.

Future advances in precision conservation

While the basic components already exist for applying precision conservation to buffer design, substantial improvements are possible that can produce even more effective and area-efficient designs and facilitate the use of a precision-conservation approach. A particularly important and challenging problem to address is the availability of sufficiently-accurate topographic data. Commonly available data sources such as 30-m digital elevation models provide a starting point, but more accurate data can yield much better results for describing critical surface-runoff patterns. Researchers have warned of accuracy limitations of digital elevation models as sources of spatial information for modeling hydrologic patterns (Walker and Willgoose, 1999; Wolock and Price, 1994).

Techniques must also be developed to better address spatial patterns of pollutant filtering from shallow groundwater. In some landscapes, groundwater flow may be the dominant pathway of pollutant transport from fields to streams (Lowrance et al., 1997). There is a dearth of information on which to base width recommendations for filtering pollutants from shallow groundwater. Spatial patterns of groundwater flow to streams has been shown to be highly variable (Bosch et al., 1994, 1996; Cooper, 1990; Haycock and Burt, 1993; Lowrance et al., 1997) and difficult to identify accurately. For lack of direct information, land elevation data might be used to indicate slope of the groundwater surface, but this approach may not be very accurate. Also, the magnitude and spatial variability of subsoil permeability and geologic materials also must be known to determine groundwater flow patterns and rates (Vidon and Hill, 2004). This general lack of detailed subsurface information prevents accurate description of spatial patterns of groundwater-runoff areas and loads to field margins. For locations where adequate subsurface information is available, a buffer filtration model, the Riparian Ecosystem Management Model, has been developed to compute pollutant filtration from groundwater (Lowrance et al., 2000).

Finally, the operational convenience of precision technologies must improve. The basic components for a precision approach to buffer design must be closely integrated into an easy-to-use information and analysis system. Greater operational convenience will come from integrating data-layer acquisition, predictive modeling, and map generation seamlessly into a GIS platform. At this time, these basic components are being developed independently and, generally, without a coordinated goal.

Summary and Conclusion

Capabilities now exist to increase the precision with which water-quality buffers are designed and established. Precision conservation enables the design and placement of variable-width buffers that match spatially-variable runoff loads at the field scale. Data sets and modeling components are currently available that would support a precision-conservation approach to buffer design. Many improvements that would enhance operational convenience and improve design accuracy are possible, and needed. A precision-conservation approach can enhance buffer projects by placing more buffer where there is greater need and by yielding better predictions of their effectiveness.

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References Cited

Barfield, B.J., E.W. Tollner, and J.C. Hayes. 1979. Filtration of sediment by simulated vegetation. I. Steady-state flow with homogeneous sediment. Transactions of the ASAE 22:540-545, 548.

Berry, J.K., J.A. Delgado, R. Khosla, and F.J. Pierce. 2003. Precision conservation for environmental sustainability. Journal of Soil and Water Conservation 58(6):332-339.

Bosch, D.D., R.K. Hubbard, L.T. West, and R.R. Lowrance. 1994. Subsurface flow patterns in a riparian buffer system. Transactions of the ASAE 37:1783-1790.

Bosch, D.D., J.M. Sheridan, and R.R. Lowrance. 1996. Hydraulic gradients and flow rates of a shallow coastal plain aquifer in a forested riparian buffer. Transactions of the ASAE 39:865-871.

Bren, L.J. 1998. The geometry of a constant buffer-loading design method for humid watersheds. Forest Ecology and Management 110:113-125.

Bren, L.J. 2000. A case study in the use of threshold measures of hydraulic loading in the design of stream buffer strips. Forest Ecology and Management 132:243-257.

Brothers, J.M. 2001. Riparian buffer planning and assessment considering topographic accuracy and microrelief. M.Sc. Thesis. Department of Biological Systems Engineering, University of Nebraska, Lincoln.

Cooper, A.B. 1990. Nitrate depletion in the riparian zone and stream channel of a small headwater catchment. Hydrobiologia 202:13-26.

Daniels, R.B. and J.W. Gilliam. 1996. Sediment and chemical load reduction by grass and riparian filters. Soil Science Society of America Journal 60:246-251.

Dickey, E.C. and D.H. Vanderholm. 1981. Vegetative filter treatment of livestock feedlot runoff. Journal of Environmental Quality 10:279-284.

Dillaha, T.A., J.H. Sherrard, and D. Lee. 1986. Long-term effectiveness and maintenance of vegetative filter strips. Bulletin 153, Virginia Water Resources Research Center, Virginia Polytechnic Institute and State University, Blacksburg, Virginia.

Dillaha, T.A., R.B. Reneau, S. Mostaghimi, and D. Lee. 1989. Vegetative filter strips for agricultural nonpoint source pollution control. Transactions of the ASAE 32:513-519.

Dosskey, M.G. 2001. Toward quantifying water pollution abatement in response to installing buffers on crop land. Environmental Management 28(5):577-598.

Dosskey, M.G., M.J. Helmers, D.E. Eisenhauer, T.G. Franti, and K.D. Hoagland. 2002. Assessment of concentrated flow through riparian buffers. Journal of Soil and Water Conservation 57(6):336-343.

Dosskey, M.G., M.J. Helmers, D.E. Eisenhauer, T.G. Franti, and K.D. Hoagland. 2003. Hydrologic routing of farm runoff and implications for riparian buffers. *In:* J.D. Williams and D. Kolpin (eds.) Agricultural Hydrology and Water Quality. American Water Research Association 2003 Spring Specialty Conference Proceedings. American Water Resources Association, Middleburg, Virginia. TPS-03-1, CD-ROM.

Fabis, J., M. Bach, and H.-G. Frede. 1993. Vegetative filter strips in hilly areas of Germany. Pp. 81-88. *In:* Integrated resource management & landscape modification for environmental protection. Proceedings of the International Symposium, Dec. 13, 1993, Chicago, Illinois. American Society of Agricultural Engineers, St. Joseph, Michigan.

Haycock, N.E. and T.P. Burt. 1993. Role of floodplain sediments in reducing the nitrate concentration of subsurface run-off: a case study in the Cotswolds, UK. Hydrologic Processes 7:287-295.

Hayes, J.C., B.J. Barfield, and R.I. Barnhisel. 1979. Filtration of sediment by simulated vegetation II. Unsteady flow with non-homogeneous sediment. Transactions of the ASAE 22:1063-1067.

Knisel, W.G. (ed). 1980. CREAMS: A field-scale model for chemicals, runoff, and erosion from agricultural management systems. Conservation Research Report No. 26. U.S. Department of Agriculture, Washington, D.C.

Larson, W.E., M.J. Lindstrom, and T.E. Schumacher. 1997. The role of severe storms in soil erosion: A problem needing consideration. Journal of Soil and Water Conservation 52:90-95.

Lowrance, R., L.S. Altier, J.D. Newbold, R.R. Schnabel, P.M. Groffman, J.M. Denver, D.L. Correll, J.W. Gilliam, J.L. Robinson, R.B. Brinsfield, K.W. Staver, W. Lucas, and A.H. Todd. 1997. Water quality functions of riparian forest buffers in Chesapeake Bay watersheds. Environmental Management 21:687-712.

Lowrance, R., L.S. Altier, R.G. Williams, S.P. Inamdar, J.M. Sheridan, D.D. Bosch, R.K. Hubbard, and D.L. Thomas. 2000. REMM: The Riparian Ecosystem Management Model. Journal of Soil and Water Conservation 55(1):27-34.

Ludwig, B., J. Boiffin, J. Chadoeuf, and A.V. Avzet. 1995. Hydrologic structure and erosion damage caused by concentrated flow in cultivated catchments. Catena 25:227-252.

Magette, W.L., R.B. Brinsfield, R.E., Palmer, and J.D. Wood. 1989. Nutrient and sediment removal by vegetated filter strips. Transactions of the ASAE 32:663-667.

McMaster, K.J. 2002. Effects of digital elevation model resolution on derived stream network positions. Water Resources Research 38(4):1-9.

Muñoz-Carpena, R. and J.E. Parsons. 2000. VFSMOD, Vol. 1.04, User's Manual. North Carolina State University, Raleigh.

National Research Council. 1997. Precision Agriculture in the 21st Century: Geospatial and Information Technologies in Crop Management. National Academy Press, Washington D.C.

Patty, L., B. Real, and J.J. Gril. 1997. The use of grassed buffer strips to remove pesticides, nitrate and soluble phosphorus compounds from water. Pesticide Science 49:243-251.

Pierce, F.J. and P. Nowak. 1999. Aspects of precision agriculture. Advances in Agronomy 67:1-85.

Renard, K.G., G.R. Foster, G.A. Weesies, D.K. McCool, and D.C. Yoder (coordinators). 1997. Predicting soil erosion by water: A guide to conservation planning with the Revised Universal Soil Loss Equation (RUSLE). Agriculture Handbook No. 703. U.S. Department of Agriculture, Washington D.C.

Schmitt, T.J., M.G. Dosskey, and K.D. Hoagland. 1999. Filter strip performance and processes for different vegetation, widths, and contaminants. Journal of Environmental Quality 28:1479-1489.

Souchere, V., D. King, J. Daroussin, F. Papy, and A. Capillon. 1998. Effects of tillage on runoff directions: consequences on runoff contributing area within agricultural catchments. Journal of Hydrology 206:256-267.

U.S. Department of Agriculture Natural Resources Conservation Service (USDA-NRCS). 1994. State Soil Geographic (STATSGO) Database: Data use information. Miscellaneous Publication No. 1492. U.S. Department of Agriculture, Washington, D.C.

U.S. Department of Agriculture Soil Conservation Service (USDA-SCS). 1968. Hydrology, supplement A to section 4 Engineering Handbook. U.S. Department of Agriculture, Washington, D.C.

Vidon, P.G.F. and A.R. Hill. 2004. Landscape controls on the hydrology of stream riparian zones. Journal of Hydrology 292:210-228.

Walker, J.P. and G.R. Willgoose. 1999. On the effect of digital elevation model accuracy on hydrology and geomorphology. Water Resources Research 35(7):2259-2268.

Wolock, D.M. and C.V. Price. 1994. Effects of digital elevation model map scale and data resolution on a topography-based watershed model. Water Resources Research 30(11):3041-3052.